VENUS INTREPID TESSERA LANDER (VITAL): A MISSION CONCEPT STUDY FOR THE NATIONAL RESEARCH COUNCIL PLANETARY DECADAL SURVEY

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ABSTRACT

NASA Headquarters commissioned the Goddard Space Flight Center (GSFC) with the Venus Intrepid Tessera Lander (VITaL) study to support the National Research Council's 2010 Planetary Decadal Survey Inner Planets Panel. The study focused on a landing on Venus tessera terrain. The tessera regions of Venus provide fundamental clues to Venus's past, but this terrain has been viewed as largely inaccessible for landed science due to the known centimeter to kilometer scale roughness. A highly capable Ring Lander has been designed to withstand landing on a block 1.3 m high that is sitting on a 30° slope without tipping over. This configuration was traded with alternate designs that had the ability to tumble. Extensive instrumentation is included in the design concept to provide high fidelity images during descent and surface operations along with extensive mineralogy and elemental measurements of the surface via a Raman/Laser Induced Breakdown Spectroscopy (LIBS) system. The VITaL concept utilizes present day technologies, and shows that a tessera landing may be feasible in the coming decade as a medium class mission.

1. SCIENCE OBJECTIVES

Venus is often referred to as Earth's sister because of their similar size and position within the solar system. Yet, despite their similar origins, the two planets have followed very different evolutionary paths. Magellan images of the surface of Venus show it to be largely covered with volcanic materials, but the distribution and timing of the volcanism is inconsistent with the plate recycling mechanism that operates on Earth today. The Deuterium/Hydrogen (D/H) ratio of the venusian atmosphere measured by Pioneer Venus and from Earth is the highest in the solar system, and is consistent with the loss of significant water over the history of the planet. Water is clearly unstable on the surface of Venus at present, and a lack of water in Venus' recent history has been invoked to explain why the planet may lack terrestrial-type plate tectonics. The ancient history of Venus, presumed to be more water rich, perhaps with an ocean and possibly habitable, can only be found in materials that predate the volcanic plains – these materials may be preserved in tessera terrain.

2. SCIENCE REQUIREMENTS

The key science driver for the Venus Intrepid Tessera Lander (VITaL) mission is to measure the mineralogy and major elemental composition of tessera terrain, which is distinct from the plains and is yet unsampled, and is essential to understanding the compositional diversity of the Venus crust. Tessera terrain composition provides critical constraints on Venus geochemistry, geodynamics, and the history of water on the planet. Near-infrared descent imaging below the clouds will provide a new dataset for Venus and enable a unique assessment of geomorphology and surface processes that can help calibrate the global Magellan radar and Venus Express (VEx) image data. High resolution imaging of these unique terrains in optical wavelengths can provide details about the scales of geomorphic roughness and localized tectonic deformation, and possibly evidence of mass wasting in areas with topographic variability. Multispectral, panoramic imaging on the surface at the centimeter scale will constrain local morphology, stratigraphy, and weathering processes. Detailed contextual imaging of the surface where geochemistry measurements are made serves as the geologist's hand lens for assessment of mineralogy and rock textures.

Compositional measurements of the atmosphere constrain atmospheric evolution, but to date, very little compositional or physical information has been garnered about the lowermost scale height (<16 km), which is key to understanding both atmospheric evolution and surface-atmosphere interactions. Another objective of VITaL is to measure noble gases and their isotopes within the atmosphere, and to measure trace gases and their isotopes and physical parameters (pressure, temperature, and wind speed) at a new place and time on Venus through the atmosphere to the surface. These compositional measurements, particularly when combined with elemental chemistry and mineralogy observations on the surface, will provide an improved understanding of surface atmosphere interactions, and may also potentially address the issue of active volcanism on Venus.

Finally, the status of the venusian interior is very poorly constrained. Orbital measurements show Venus to lack a magnetic field, which supports the conclusion that Venus lacks a dynamo at present. This result can be verified with surface measurements of any ambient field. Mantle overturn events, such as that hypothesized to have emplaced the Venus plains, may have been associated with an ancient active dynamo, traces of which may be present as remanent magnetism in Venus rocks.

3. TESSERA LANDING CONDITIONS

A typical VITaL landing error ellipse on the order of 75 km (E-W) by 150 km (N-S) is adequate for targeting tessera terrain, which is contiguous over hundreds to thousands of kilometers. An example landing site was selected in the continent-size tessera highlands of Ovda Regio. This near-equatorial site maximizes optimal lighting conditions for the descent images. A landing ellipse this size can access many regions within Ovda that are dominated by slopes <30° (at the kilometer scale) and avoid intra-tessera volcanic plains, which are not a desired chemical target. Improved knowledge of sub-kilometer surface hazards may place more strict requirements on landing precision.

The primary challenges to landing on tessera terrain are surface roughness and slopes. These characteristics can be assessed using the Magellan altimetry data set (~10 km spatial resolution with ~80 m vertical precision), SAR images (75 m/pixel) and SAR radargrammetry data (~2 km spatial resolution). These data show average kilometer scale slopes in tessera terrain are ~5-10° and areas with slopes >10° are limited (0-5% of the surface; Fig. 1; 1,2). These data do not measure small scale faults observable in the SAR imagery. As on Earth, fresh extensional fault scarps are predicted to lie at 60-70° slopes, however, processes of mechanical weathering will serve to reduce these slopes to the angle of repose (~35°) on both planets. Measurements of 170 faults across Venus using radargrammetry yield an average slope of 36+/-2° [3]. Even if all slopes on Venus tessera terrain were fresh, examination of a typical landing ellipse in Ovda (e.g., Fig. 1) shows these slopes comprise only 1% of the landing ellipse. Meter scale roughness can introduce additional slope elements. Radar reflectivity data of tessera terrain is similar to that from terrains on Earth with roughness at the 10s cm scale [4,5], perhaps similar to the Venera 9 landing site, where a rock tilted the lander an additional 10° [6,7]. As weathering on Venus is largely limited to mass wasting, tessera surfaces similar to scree slopes in arid regions on Earth are expected, where submeter scale rocks form talus deposits at the angle of repose. While better (~100X) topography and imaging of potential landing sites will reduce landing risk, the VITaL mission is robust enough to tolerate tessera slopes ≤60°, which should accommodate 99% of expected slopes and rock sizes.

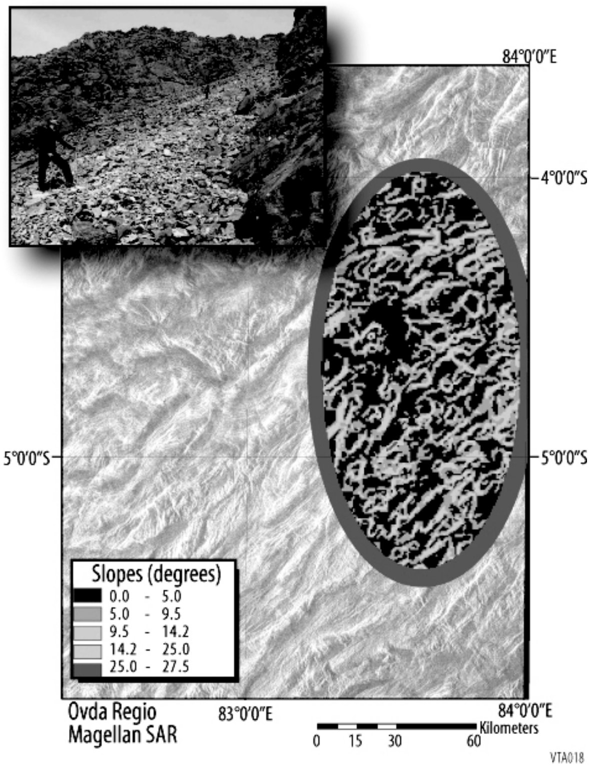

Fig. 1: Synthetic Aperture Radar (SAR) and surface slopes in Ovda Regio. Slopes are calculated within an example VITaL landing ellipse of 75 X 150 km. Slope data are derived from Magellan radargrammetry data [8] and have a resolution of ~2 km. Kilometer-scale average slopes for this region are 6 ± 4° with a maximum slope of 28°. Slopes shown here are typical of tesserae generally. Inset: terrestrial example of ~20° slope. Fracturing of rocks and mass wasting may produce similar surfaces in Venus tessera highlands.

4. MISSION OVERVIEW

The VITaL Mission's space segments consist of a probe and flyby carrier spacecraft that is also used as a communications relay. The probe is comprised of two top-level elements: the lander, and the Entry and

Descent Element (EDE), which includes the aeroshell and parachute systems.

Carrier Spacecraft: The three-axis stabilized carrier spacecraft performs three functions: 1) delivers the probe on an interplanetary trajectory to Venus, 2) releases the probe on an appropriately pointing trajectory to enter the Venus atmosphere, and 3) acts as a communication relay between the lander and the Earth. Because of the flyby trajectory, the required fuel mass is relatively small, thermal and power tasks are manageable, and electronics and communication systems are straightforward. The drivers for the carrier spacecraft design include spinning up the probe to 5 RPM prior to release and having a robust structure to support the probe.

Probe: The probe is released from the carrier 5 days before reaching the Venus atmosphere. The communications system is switched on 1 hour before encountering the atmosphere and transmits continuously. The aeroshell is designed with carbon phenolic material that ablates upon entry into the Venus atmosphere, where the probe experiences a deceleration of 200 g. The heat shield is jettisoned minutes after the parachute system on the backshell is deployed (at an altitude of ~60 km). Following this operation, the backshell and parachute system are released from the lander. *In situ* atmospheric structure, neutral mass spectrometer, and tunable laser spectrometer measurements are conducted throughout descent, and images are acquired from the NIR camera from ~15 km to the surface. The lander uses drag plates to slow the descent to the surface and crushable material to help absorb the kinetic energy of landing. Landing at 9 m/s produces an 86 g load on the pressure vessel. Once safely on the surface, the lander collects the Raman/LIBS measurements, Raman/LIBS context images, and panoramic images.

5. INSTRUMENTATION

Neutral Mass Spectrometer (NMS): provides *in situ* measurement of noble gas isotopes and multiple trace gas mixing ratios. The NMS instrument consists of three modules: an ion source to convert gas phase sample molecules into ions; a mass analyzer, which applies electromagnetic fields to sort the ions by mass; and a detector, which measures the abundance of each ion present.

Tunable Laser Spectrometer (TLS): measures trace gases, including multiple isotopes of sulfur and hydrogen-bearing species. Of particular interest, the TLS measures the Deuterium/Hydrogen (D/H) ratio in atmospheric water via measurement of molecular line parameters for infrared molecular absorption lines. Utilizing extremely small tunable laser spectrometers with room temperature laser detector arrays in a Herriott cell configuration, TLS provides multi-wavelength *in situ* measurements of the Venusian atmosphere. TLS is combined with the NMS, sharing common electronics and piping, but is listed separately since each spectrometer has unique measuring timelines.

Raman/Laser Induced Breakdown Spectrometer (LIBS): is a combined instrument, utilizing a single laser and a single telescope to provide mineralogy and elemental chemistry of surface rocks. Raman illuminates the remotely located (~2 to 3 m) sample with a low power 532 nm laser pulse and observes the scattered return (Raman wavelength shift) to determine the vibrational modes of the chemical bonds in the target. LIBS utilizes this same laser at a higher power level (1064 nm) to vaporize and ionize a portion of the target material, creating a plasma. By measuring the intensity and wavelength of the photons emitted by the plasma, the elemental chemical composition of the sample is inferred. The instrument accesses the sample area through a viewing window on the side of the lander and requires a 6.5 cm clear aperture. The Raman/LIBS spectrometer is designed to have a 300 micron spot size. The focal point of the spectrometer utilizes a 3000 x 96 pixel CCD. The spectrometer and context camera are mounted on a bench that pans +/-10°. The 20 Hz source laser provides 15 mJ of 532 nm and 50 mJ of 1064 nm focused illumination. The optical schematic is shown in Fig. 2. The size of the laser and receiver are scaled up from Mars Science Laboratory ChemCam and ExoMars versions of these instruments, though they are less sensitive compared to other studies of Raman/LIBS applications at Venus (Table 1). This sizing increase versus Mars missions is to account for the attenuation of the Venus CO_2 atmosphere. The laser is coupled to the common optics with a flexible optical fiber link. Landing in the tessera will result in uneven slopes and unpredictable distances between the lander and the measured rocks. Therefore a mechanism is built into the optical train that moves the common (to the receiver and laser source) primary mirror to enable the laser and receiver to focus anywhere from 2 to 3 meters away (this only requires +/-5 mm of travel which could easily be expanded). Focus is achieved by comparing return signal strengths. Raman/LIBS measurement locations are outside the outer landing ring and within the FOV of the panoramic camera (Fig. 3). Six inches of clearance are allowed above the outer ring to enable some unplanned plastic deformation of the ring due to adverse landing conditions.

Raman/LIBS Context Imager: is co-aligned with the Raman/LIBS spectrometer. The spectrometer optics and the imager are located on a rotatable bench. The imager utilizes its own 3 cm viewport. The Raman/LIBS context camera has a narrow field of view of 4.6° x 4.6° (20 cm x 20 cm spot at 2.5 meters). This imager captures the geological context of the Raman/LIBS measurements. Its FOV overlaps with the panoramic camera (Fig. 3) and descent images. The images taken by this camera are shown in comparison to the Raman/LIBS measurement locations in Fig. 4. Future studies will need to address potential interference from dust disturbed at touchdown, particularly the possibility of dust adhering to the window.

Descent Imager: points in the nadir direction and acquires images during descent (Fig. 3). Images of the Raman/LIBS sample area are recorded during the final moments of descent, providing additional information about the site prior to landing (Fig. 5). The camera requires a 2.4 cm viewing window. The camera optics provide a 40° x 40° FOV with a 1024 x 1024 array, resulting in 0.84 m pixel size at 1 km.

Table 1. Sizing Scale of Baseline Raman/LIBS compared to other studies of Raman/LIBS

Reference	1064 nm energy LIBS (mJ)	532 nm energy Raman (mJ)	Distance (m)	Telescope Dia (cm)	Analytical Spot Size (mm)	Telescope Dia2 x Laser Energy / (Distance2)	Ratio with Sharma
Sharma, et al. [9]	50	15	1.5	12.7	0.25	3584.2	1.0
Clegg, et al. [10]	50	35	1.7	12.7		2891.6	0.8
Wiens, et al. [11]	50	35	8.6	12.7	0.60	109.0	0.0
Baseline	50	15	2.5	6.5	0.30	338.0	0.1

Panoramic Imager: points along the horizon in four orthogonal directions and acquires images once landing has occurred. The panoramic camera has a mechanized filter wheel with five filters and one neutral density filter. The filters are 550, 650, 750, 850, 1000 nm, each with bandwidth of 20-30 nm. The camera has a FOV 25° below the horizon and 10° above the horizon by 60° wide (Fig. 3). Four windows in the cupola on the top of the pressure vessel enable a 240° view. A mechanism within the pressure vessel rotates a mirror to allow the camera to sequentially acquire images through each of the four windows. One of the panoramic windows has a clear view of the Raman/LIBS measurement locations with a pixel resolution of 0.4 cm at a 3 m distance. Like the Raman/LIBS context imager, future studies will need to address potential interference from dust disturbed at touchdown, particularly the possibility of dust adhering to the window, though being located on the top of the lander on the other side of the drag plate should decrease this sensitivity.

Triaxial Fluxgate Magnetometer: determines the presence or absence of a planetary magnetic field. This instrument is inside the lander; no boom is required. This is sufficient, since planetary and/or local rock magnetic fields of interest are expected to be orders of magnitude larger than typical electronics fields.

Atmospheric Structure Investigation (ASI): has sensors located on the outside of the lander to characterize gross atmospheric properties, including temperature and pressure. This package consists of a temperature sensor, a pressure transducer, anemometer, and an accelerometer. The nominal implementation concept does not utilize a boom or mast; exact implementation of this instrument package is left to a future study.

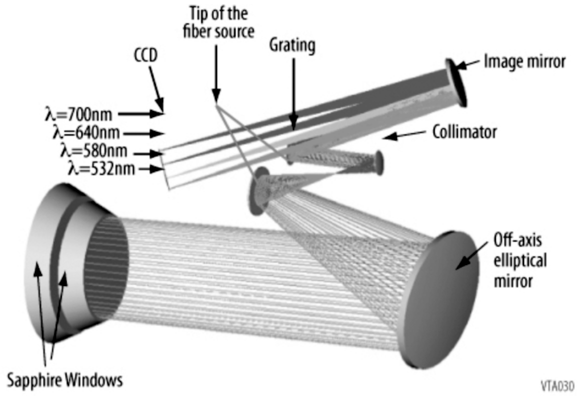

Fig. 2: Optical schematic for the LIBS/Raman spectrometer

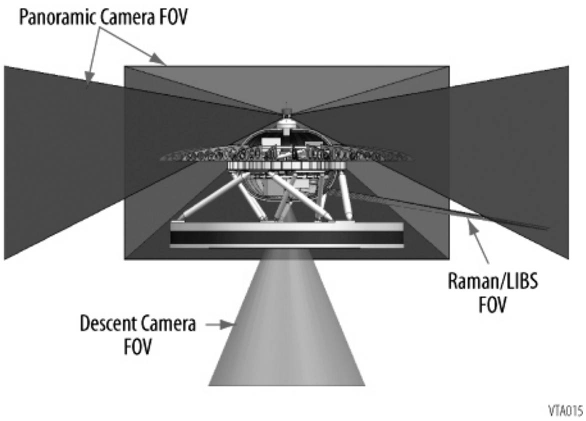

Fig. 3: Fields of view for each of the camera systems

Fig. 4: Raman/LIBS context images and sample locations

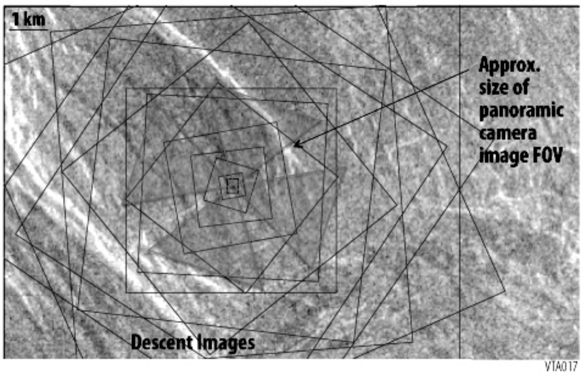

Fig. 5: Descent Camera Image Footprints

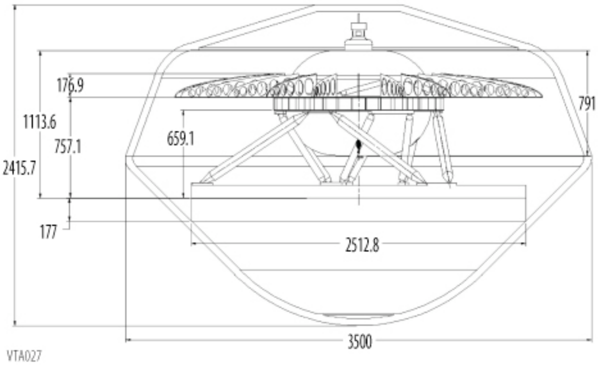

Fig. 7: Lander in aeroshell (in mm)

6. MECHANICAL DESIGN

The mechanical system is designed to safely transport the instrument suite to a tessera region on the Venus surface. The mechanical design of the lander concept (Fig. 6) is driven by the two most challenging requirements: the high deceleration loads expected during entry into the Venus atmosphere, and operational stability of the system after landing on an unknown terrain. Due to the uncertainty about terrain conditions at the landing site, proposed designs were selected to provide a high level of assurance of success even if the terrain is extremely uneven. It was assumed that the worst-case scenario for this design was landing on a 30° slope and with the high side of the lander striking a 1.3 m high block. The Ring Lander design meets the instrument suite field-of-view (FOV) requirements for ground imaging during descent and landing, and for the Raman/LIBS instrument (Fig. 3). The panoramic camera FOV requirement is met using the cupola structure at the top of the pressure vessel (Fig. 3), and must include the Raman/LIBS sample location. The structural system design accommodates the high performance thermal control system, which includes isolation and insulation systems and phase change materials.

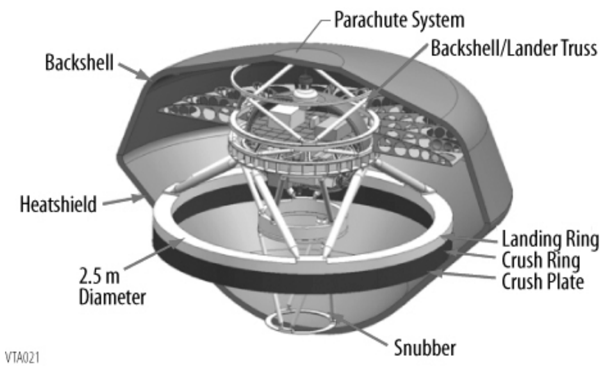

Fig. 6: Lander design

The probe primary structure is a hermetically sealed pressure vessel to reduce the transfer of thermal energy and prevent the influx of Venus atmosphere. Fig. 8 shows interior details of the pressure vessel. The entire packaged lander is designed to fit into an aeroshell system (Figs. 6, 7) and survive the 200 g loads expected during entry into the Venus atmosphere and the 83 g loads expected at impact on the Venus surface. The stability of the lander is based on a high-mass outer ring, lowering the center of gravity and providing a stable base upon landing. The design also includes an inner ring to protect the probe from protruding objects during landing. The inner ring is recessed from the main landing ring and may require some crushable material depending upon the analysis. The current design concept has a static tip-over stability of up to 72.7° (Fig. 9). The system allocation for this static tip angle includes: 30° for macro scale slopes, 30° for a 1.3 m block, 10° for dynamic landing conditions, and 2.7° unallocated (Fig. 10). The primary structure was designed to handle the 200 g deceleration loads on the probe during the Venus atmospheric entry phase of mission timeline and a 9 m/s expected impact velocity for landing. The design provides deceleration using a crushable titanium foam ring that reduces the expected landing loads to 83g.

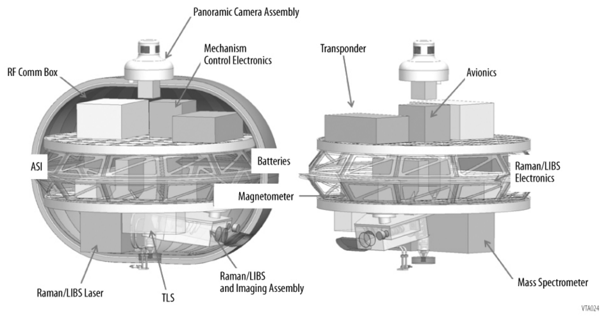

Fig. 8: Interior details of the pressure vessel

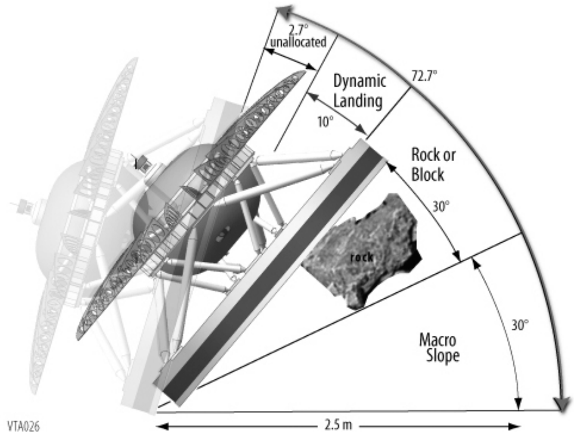

Fig. 9: Lander showing tilt scenario

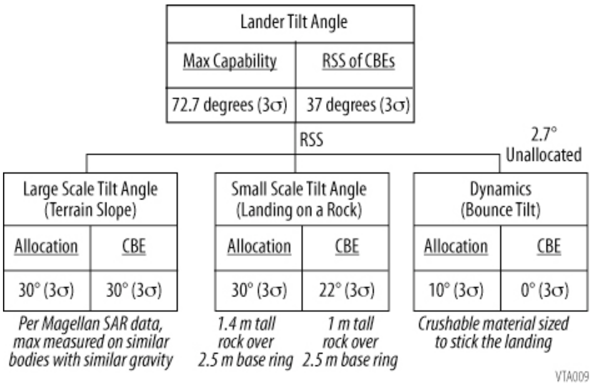

Fig. 10: Tilt angle budget for lander

7. MECHANICAL ANALYSIS

The Ring Lander has been analyzed to verify that the design concept meets structural load and stability requirements during atmospheric entry and landing. Loads and stiffness requirements were both assumed and derived. The basic load cases are atmospheric entry, level landing, and landing on a macro and micro slope (30° inclined assumed). The crushable material (titanium foam) was sized for both a full ring contact (highest deceleration) landing and a partial ring contact (crushable material thickness driver), Fig. 11. The analysis used a landing velocity of 10 m/s, though for the actual lander, this was calculated as 9 m/s and could be dropped to 7 m/s by maximizing the drag plates in the aeroshell (1/2 the energy).

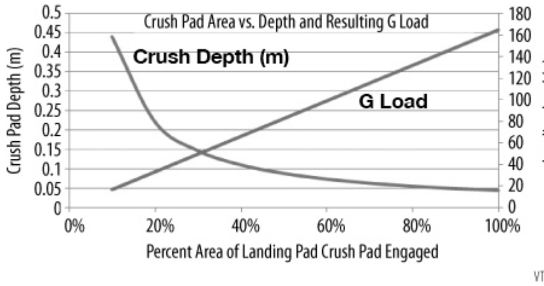

Fig. 11: Crushable material depth versus G load

8. MECHANISMS

Each VITaL mechanism (Fig. 12) comprises a basic mechanical design with extensive flight heritage (TRL 6). The position resolutions, listed in represent easily attainable target values for these types of mechanisms. All drive mechanisms comprise a stepper motor coupled to an appropriately-sized planetary gear set. A separate mechanisms control electronics box is required to control the actuators.

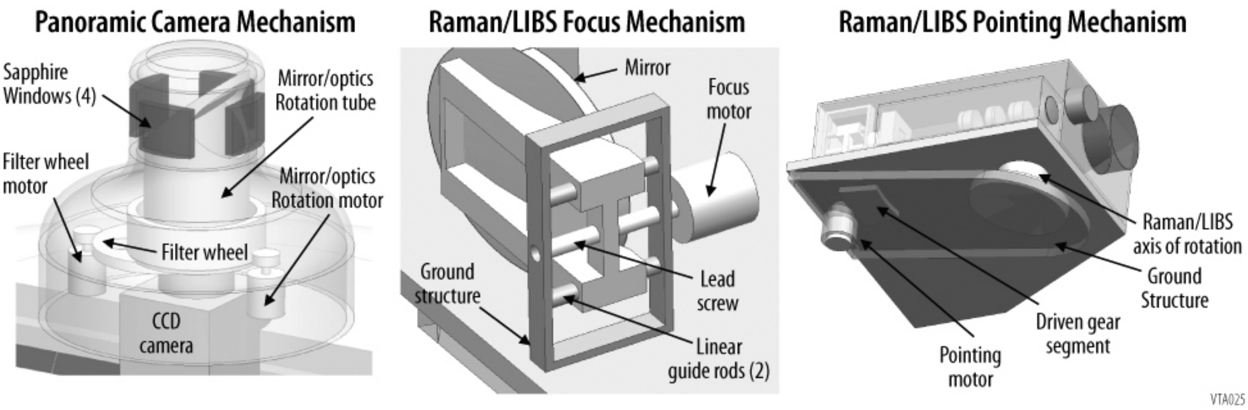

Fig. 12: VITaL mechanisms

9. THERMAL DESIGN AND ANALYSIS

The Venus atmosphere presents a unique thermal environment. The temperature at the surface is 447° C, with a pressure of approximately 81 bar at the surface in the Ovda Regio (approximately 2 km above mean planetary radius). The three-hour mission life includes a one-hour descent through the atmosphere, and 2 hours spent on the Venus surface. The operational temperature limits of the avionics and instruments are assumed to be -20° C to 40° C, and their total heat dissipation is expected to be 239 W on the surface. The interior of the lander is pressurized at 1 bar, and natural convection is assumed to take place inside the pressure vessel. The thermal strategy for this design concentrates the cooling directly at the electronics, and thermally isolates the two electronics decks from the rest of the lander. Phase change material (PCM) is embedded inside the decks to provide maximum conduction to the electronics, which are mounted on top of the decks. Lithium nitrate trihydrate (LNT) is selected as the PCM. LNT was flown on the Venera landers, and minimizes mass and volume. Fig. 13 shows a graph of temperatures during the three-hour mission. There are multiple heat leaks into the pressure vessel, as quantified in Fig. 14. Seven sapphire windows are required for conducting science observations from within the lander. Each window is double paned, with a small air gap between for thermal insulation.

10. COMMUNICATIONS DESIGN

The VITaL mission duration, from entry to end-of-mission, lasts approximately three hours. During that time, data are collected at variable rates to maximize performance and transmission. An S-band communication link is baselined, since the Venus atmospheric attenuation from the surface is small compared to other frequency bands (less than 3 db for elevation angles above 10°).

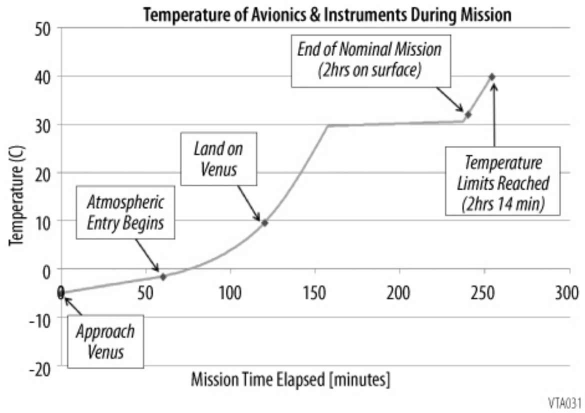

Fig. 13: Lander temperatures during the mission

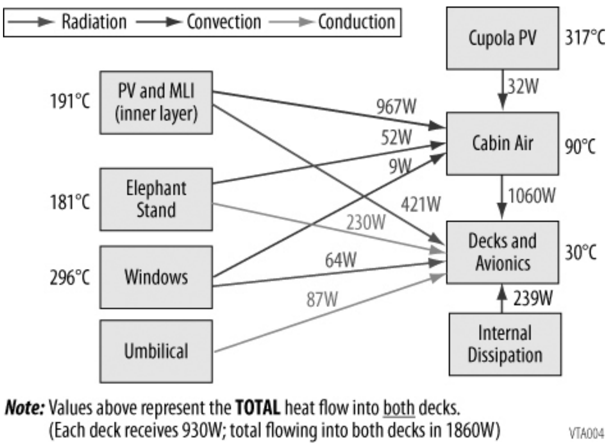

Fig. 14: Avionics heat flow

The communication system aboard the probe is designed to maximize data transmission throughout the full mission duration. The system takes into consideration the flight trajectory and the changing uplinked science data quantity, depending on the angle of the landing site versus the carrier spacecraft. The system also allows for delayed uplink to the carrier spacecraft in the case of local topography blockages. The VITaL probe communications system consists of an S-band transponder, which allows commanding and two-way Doppler, as well as a 50 W Traveling Wave Tube Amplifier (TWTA) and supporting radio frequency (RF) components for uplink/downlink capabilities, as shown in Fig. 15 and 16.

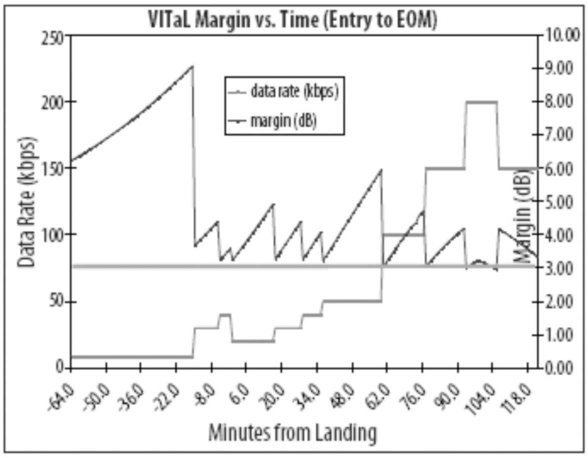

Fig. 15 Communications capability

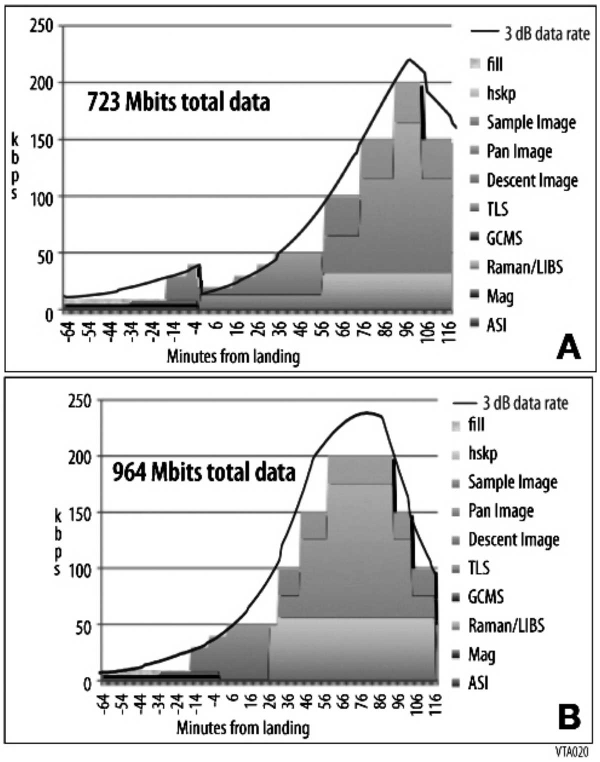

Fig. 16: Total data upload from the lander (A) 40° slope (B) level slope

11. ALTERNATIVE LANDER DESIGN

A Cage Lander was developed as an alternative to the Ring Lander, with a rotatable pressure vessel protected on all sides by structure (Fig. 17). This design has the advantage of operating even if it flips upside down. However, because structural members (the cage) fully envelope the pressure vessel and because the pressure vessel will rotate within the cage, panoramic camera, omni antenna, and Raman/LIBS instrument FOVs are potentially affected. Measures may be taken to ensure adequate science can be returned (e.g., adding actuators to move the cage structure, post-landing, away from the "up" side of the lander to ensure adequate instrument and omni FOVs).

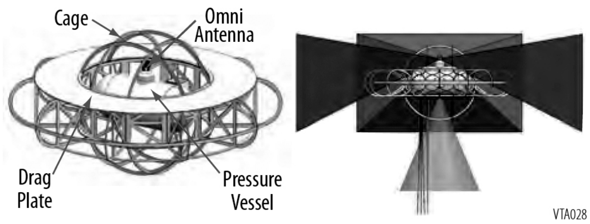

Fig. 17 Cage design A, left, structure, right, FOV

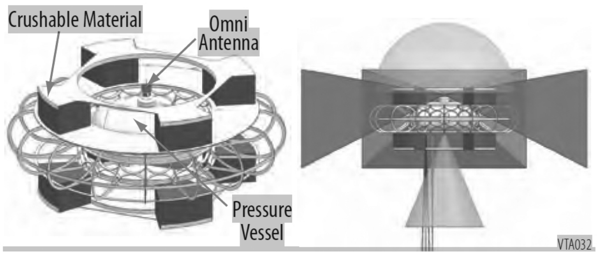

Fig. 18 Cage design B, left, structure, right, FOV

Dynamically, the cage design need not fully absorb the impact energy because there is no lost capability if it bounces and flips. This allows for a less rigid structural design that may include some amount of crushable material. A second version of the cage design has been generated that has an annulus region of crushable material above and below the pressure vessel (Fig. 18). Using crushable material rather than the cage to protect the pressure vessel enables the omni antenna to function without the heavy communication uplink penalty of the cage (which acts as a reflector for the long wavelength S-Band). Fig. 17b and Fig. 18b illustrate the instruments' FOV for each cage lander concept, although further study is needed to fully compare each cage design. Both cage designs take advantage of the pressure vessel's ability to rotate to an "omni-up" pose within the cage. This controlled rotation is accomplished by incorporating a motorized rotating counter-weight within the pressure vessel that will alter the vessel's center of gravity, causing the pressure vessel to rotate. Both cage landers also have the advantage of being lighter than the Ring Lander, possibly allowing a smaller launch vehicle. The Ring Lander was chosen as a baseline due to its lower complexity and cost, but there are advantages to the other designs that warrant further consideration.

12. CONCLUSIONS

The tessera regions of Venus provide fundamental clues to Venus's past, and are recognized as a high priority science target by the Venus community (VEXAG), but this terrain has been viewed as largely inaccessible for landed science due to the known roughness. We have designed a robust lander capable of landing safely in the tessera terrain conducting surface and atmospheric science, and transmitting all data back to the telecom relay spacecraft. This design is shown to be technically feasible with present-day technologies.

Stereo SAR kilometer-scale topography data from Magellan show that highlands-like regions typically have macro slopes of less than 30°. Block sizes of terrestrial analogue regions are typically less than 1 m, suggesting the VITaL 1.3 m allowance is more than adequate. This paper examined the possibility of landing in the highlands of Ovda Regio because its location near the equator ensures that a mission scenario could be found with excellent lighting conditions. Several possible landing ellipses were found that had average slopes on the km scale of less than 30° and do not contain intra-tessera plains.

Extensive instrumentation is included in the design concept to provide high fidelity context images along with extensive mineralogy and elemental measurements via a Raman/LIBS system. The Raman/LIBS system sizing was explored and a Raman/LIBS laser and receiver telescope were sized. The system is smaller than some laboratory versions due to volume and power constraints, but there is a healthy amount of trade space open to optimize this system. The lander can land on a block 1.3 m high that is sitting on a 30° slope without flipping or tumbling. Mechanically surviving landing on steep slopes is not the only characteristic to consider when landing in the tessera. The data uplink to the carrier spacecraft also becomes an important driver for landings on slopes. For local slopes above 40°, part of the lander's ~2 hour lifetime at the landing site can be blocked by the surrounding terrain. Tolerating some blockage (which could occur at the beginning or end of the two hours) allowed more data return than altering the carrier spacecraft trajectory to a higher altitude and lowering the uplink rate). Therefore, the collected science data are prioritized on the lander before transmission to ensure the highest priority data reaches the carrier spacecraft.

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